Direct Power Control Space Vector Modulation Technique Suitable for Turbines Operating at Variable Speeds

Parash Acharya, Paul Gaynor
Department of Electrical and Computer Engineering
University of Canterbury, Christchurch, New Zealand
Email:acharya.parash@gmail.com

***Abstract*—This paper presents the analysis of a direct power control technique and model using space vector modulation. Voltage based Direct Power Control Space Vector Modulation for variable speed turbine is achieved. Rectifier space voltage vectors relative to the output DC voltage (for active power control) and zero reactive power (for Unity Power Factor operation) are used to control three phase rectifier switches. This technique is suitable for boosting the generator voltage within a single stage along with active Power Factor Correction (PFC).**
keywords: Direct Power Control Space Vector Modulation, Unity Power Factor, Power Factor Correction, Space Voltage Vector.

I. Introduction

Direct Power Control Space Vector Modulation (DPC-SVM) is based on instantaneous active and reactive power control loops[1]. In this technique, switching states are selected from a switching table based on instantaneous errors between commanded and estimated values of active and reactive power. The major outcome of DPC-SVM is to boost the DC voltage to a constant level while maintaining a Unity Power Factor (UPF) condition. DC voltage is stabilized by controlling the active power while UPF is achieved by keeping the reactive power to zero within the control loop.
Generally, there are two techniques used for voltage control PWM rectifiers: 1. Voltage Oriented Control (VOC) and 2. Direct Power Control (DPC). In VOC, UPF is achieved when the line current vector is aligned with the phase voltage vector. This is obtained when the quadrature component of current (i_q) is set to zero. A rotating coordinate transformation is required in order to achieve the value of i_q which is the major disadvantage of using VOC [2]. Compared to VOC, the DPC strategy does not require a rotating coordinate transformation. Generally, there are two types of DPC technique: 1. Voltage based DPC (V-DPC) and 2. Virtual Flux based DPC (VF-DPC). In V-DPC, real and reactive powers (p and q) drawn from the three phase power input are calculated using the values of the dc link voltage, rectifier switching states and line currents (i_a, i_b and i_c). Whereas, in VF-DPC, the phase voltages are estimated as the sum of rectifier input voltage and voltage drop across line reactors [3].

II. Basic Controller Configuration

The basic configuration for three phase V-DPC PWM rectifiers is as shown in Figure 1. The dc bus voltage is regulated by adjusting the active power, and UPF is achieved by controlling the reactive power to be zero. The active power reference (p_{ref}) is provided from outer Proportional Integral (PI) controller of the dc bus voltage (V_{dc}). The reference reactive power command (q_{ref}) is normally set to zero for UPF. Errors between reference and estimated feedback powers are the inputs for the hysteresis comparators and are digitized to the signals d_p and d_q. The phase of the power source voltage vector is converted into a digitized signal and for this purpose, stationary coordinates are divided into 12 sectors as shown in Figure 2[3].

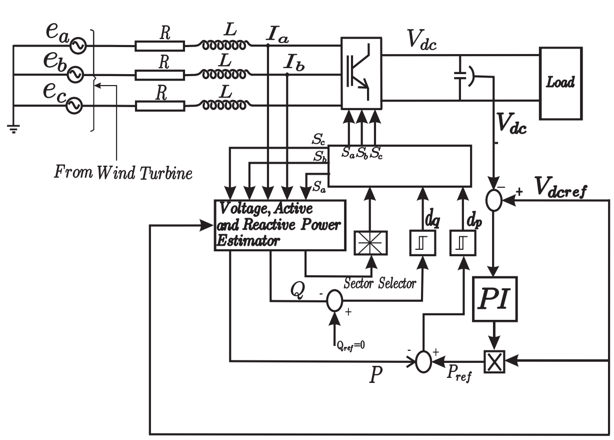

Fig. 1: configuration of DPC for three phase PWM Rectifiers

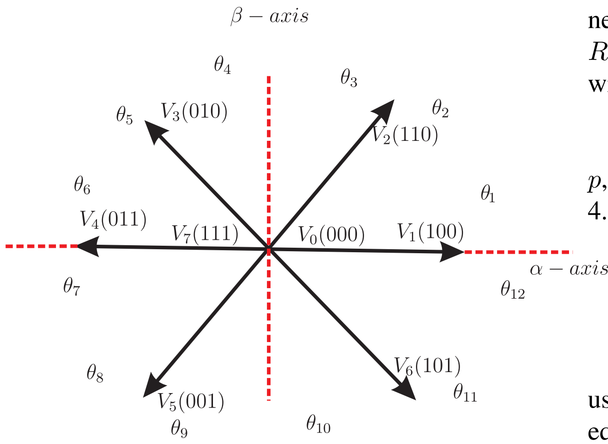

Fig. 2: Twelve Sectors in stationary coordinates and Rectifier Voltage Vectors

III. Phase voltages and active and reactive Power Estimation for voltage sensorless operation

The instantaneous apparent power($\vec{s}$) can be expressed in terms of active(p) and reactive(q) powers as in equation 1[3].

$$\vec{s} = v\vec{i} = p + jq = e_a i_a + e_b i_b + e_c i_c + j\frac{1}{\sqrt{3}} [(e_b - e_c)i_a + (e_c - e_a)i_b + (e_a - e_b)i_c] \quad (1)$$

where, e_a, e_b and e_c are instantaneous phase voltages from three phase synchronous Wind Generator (WG) and i_a, i_b and i_c are instantaneous phase currents. In-order to achieve voltage sensorless operation, the active and reactive power can be estimated in terms of the switching state of the converter, three phase line currents, dc bus voltage, and inductance of the reactors, and can be expressed as in equation 2 and equation 3[3]. Sensorless control is normally desired in order to improve the system reliability against electrical noises to the lines, fault in the lines etc.

$$p = L(\frac{di_a}{dt}i_a + \frac{di_b}{dt}i_b + \frac{di_c}{dt}i_c) + V_{DC}(S_a i_a + S_b i_b + S_c i_c) \quad (2)$$

$$q = \sqrt{3}(L\frac{di_a}{dt}i_c - \frac{di_c}{dt}i_a) - \frac{1}{\sqrt{3}}V_{DC} [S_a(i_b - i_c) + S_b(i_c - i_a) + S_c(i_a - i_b)] \quad (3)$$

Equation 2 and equation 3 show that the estimating equation for p and q have to be changed according to the switching state of the converter. Line resistance (R) also needs to be considered while estimating active power, but practically it is neglected assuming that the power dissipated in R is much lower than the active power associated with the dc bus and inductance of the reactors.

e_α and e_β can be estimated using the values of p, q, i_α and i_β and can be calculated as in equation 4.

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \frac{1}{i_\alpha^2 + i_\beta^2} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (4)$$

Finally, voltages e_a, e_b and e_c can be estimated using the Reverse park transformation as shown in equation 5.

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} \quad (5)$$

Similarly, voltage sensors can also be replaced by virtual flux estimators [1]. In this method, the voltages imposed by line power in combination with the ac-side inductors are assumed to be quantities related to a virtual ac motor. Further information of this method can be found in [1].

IV. Switching Table Development

The change in active and reactive power in terms of the generator voltage and rectifier voltage vector in the stationary $\alpha - \beta$ coordinate system can be expressed as in equation 6 and equation 7 respectively [4].

$$\triangle p = \frac{t_s}{L}[(e_\alpha^2(k)+e_\beta^2(k))-(e_\alpha(k)v_\alpha(k)+e_\beta(k)v_\beta(k))] \quad (6)$$

$$\triangle q = \frac{t_s}{L}[e_\alpha(k)v_\beta(k) - e_\beta(k)v_\alpha(k)] \quad (7)$$

where, $v_\alpha(k)$ and $v_\beta(k)$ are the rectifier voltage vectors at k^{th} iteration and t_s is the sampling time. Hence, for controlling the instantaneous active and reactive powers, there are basically six non-zero vectors and two zero vectors as shown in Figure 2. For the eight states of the rectifier, there are eight different ways of selecting the corresponding switching states which controls the evolution of active and reactive power, and are given by the expressions as in equation 8 and equation 9.

$$\triangle p_i = \frac{t_s}{L}[(e_\alpha^2 + e_\beta^2) - (e_\alpha v_{\alpha i} + e_\beta v_{\beta i})] \quad (8)$$

$$\triangle q_i = \frac{t_s}{L}[v_\alpha v_{\beta i} - v_\beta v_{\alpha i}] \quad (9)$$

where, i = 0,1,2,....,7.

The voltage vectors in the $\alpha - \beta$ coordinate system can be represented as in equation 10.

$$E_{\alpha\beta} = \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{10}$$

The vector e$_\alpha$ and e$_\beta$ is represented as in equation 11 in terms of RMS value of line voltages.

$$e_{\alpha\beta} = \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \begin{bmatrix} e\cos\theta \\ e\sin\theta \end{bmatrix} \tag{11}$$

where, e is the RMS value of line power source voltage and θ is the angular position of voltage source vector in the $\alpha - \beta$ coordinate system which is defined as in equation 12.

$$\theta = \tan^{-1}(\frac{e_\beta}{e_\alpha}); 0 \leq \theta \leq 2\pi \tag{12}$$

For rectifier voltage vector (v), the space vector representation of the seven converter switching states and its corresponding v$_\alpha$ and v$_\beta$ component values are as shown in Table I

TABLE I: Rectifier Voltage Space Vectors

v$_i$	v$_{sa}$	v$_{sb}$	v$_{sc}$	v$_{s\alpha}$	v$_{s\beta}$
0	0	0	0	0	0
1	$\frac{2}{3}V_{dc}$	$-\frac{1}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	$\sqrt{\frac{2}{3}V_{DC}}$	0
2	$\frac{1}{3}V_{dc}$	$\frac{1}{3}V_{DC}$	$\frac{2}{3}V_{DC}$	$\frac{1}{\sqrt{6}}V_{DC}$	$\frac{1}{\sqrt{2}}V_{DC}$
3	$-\frac{1}{3}V_{DC}$	$\frac{2}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	$-\frac{1}{\sqrt{6}}V_{DC}$	$\frac{1}{\sqrt{2}}V_{DC}$
4	$-\frac{2}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	$-\sqrt{\frac{2}{3}V_{DC}}$	0
5	$-\frac{1}{3}V_{DC}$	$-\frac{1}{3}V_{DC}$	$\frac{2}{3}V_{DC}$	$-\frac{1}{\sqrt{6}}V_{DC}$	$-\frac{1}{\sqrt{2}}V_{DC}$
6	$\frac{1}{3}V_{DC}$	$-\frac{2}{3}V_{DC}$	$\frac{1}{3}V_{DC}$	$\frac{1}{\sqrt{6}}V_{DC}$	$\frac{1}{\sqrt{2}}V_{DC}$

The rectifier voltage in the $\alpha - \beta$ plane is given as in equation 13.

$$|v_{\alpha\beta}| = \sqrt{\frac{2}{3}}v_{dc} \tag{13}$$

The normalized value of the change in active power ($\triangle p_i$) is derived from equation 8 and equation 11 and is written in equation 14.

$$\bar{\triangle p_i} = \frac{\triangle p_i}{\frac{t_s}{L}|e_{\alpha\beta}||v_{\alpha\beta}|} \tag{14}$$

Finally, from equation 11 and equation 14, the normalized value of active power in terms of the rectifier voltage vector is obtained as in equation 15.

$$\bar{\triangle p_i} = \frac{|E_{\alpha\beta}|}{|V_{\alpha\beta}}| - [cos\theta\bar{v_{\alpha i}} + sin\theta\bar{v_{\beta i}}] \tag{15}$$

Similarly, the change in normalized reactive power ($\triangle q_i$) deduced from equation 9 and equation 11 is given by equation 16.

$$\bar{\triangle q_i} = \frac{\triangle q_i}{\frac{t_s}{L}|e_{\alpha\beta}||v_{\alpha\beta}|} \tag{16}$$

Hence, from equation 11 and equation 16, the normalized value of reactive power can be obtained as shown in equation 17.

$$\bar{\triangle q_i} = cos\theta\bar{v_{\beta i}} - sin\theta\bar{v_{\alpha i}} \tag{17}$$

From equation 15 and equation 17 respectively, it can be seen that the change in reactive power has a sinusoidal waveform whereas change in the active power has a shifted magnitude sinusoidal waveform.

In order to ensure the smooth control of the instantaneous active and reactive power during each sector, the best rectifier voltage is selected among eight different possible states. The rectifier voltage vectors are selected according to the voltage vector position and change in active and reactive powers during each sector. The commands of reference reactive power q_{ref} (set to zero for UPF) and active power p_{ref} (delivered from the outer PI-DC voltage controller) are compared with estimated q and p values in the reactive and active power hysteresis controller respectively. The digitized output signal of the active power is defined by equation 18.

$$d_p = 1 for p < p_{ref} - H_P \tag{18a}$$
$$d_p = 0 for p > p_{ref} - H_P \tag{18b}$$

where, H_p is the hysteresis control band for the active power.

Similarly, the digitized output signal of reactive power controller is defined as in equation 19.

$$d_q = 1 for q < q_{ref} - H_q \tag{19a}$$
$$d_q = 0 for q > q_{ref} - H_q \tag{19b}$$

where, H_q is the hysteresis control band for the reactive power.

Hence, according to the digitized variables d_p, d_q and the voltage vector position, appropriate switching states are generated through a look up table which is as given in Table II. This is also known as the classical table and was initially proposed by Noguchi, et al [3].

TABLE II: The Switching Table of the DPC-SVM

d$_p$	d$_q$	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
0	0	v$_2$	v$_1$	v$_1$	v$_6$	v$_6$	v$_5$	v$_5$	v$_4$	v$_4$	v$_3$	v$_3$	v$_2$
0	1	v$_3$	v$_2$	v$_2$	v$_1$	v$_1$	v$_6$	v$_6$	v$_5$	v$_5$	v$_4$	v$_4$	v$_3$
1	0	v$_0$	v$_1$	v$_7$	v$_6$	v$_0$	v$_5$	v$_7$	v$_4$	v$_0$	v$_3$	v$_7$	v$_2$
1	1	v$_0$	v$_0$	v$_7$	v$_7$	v$_0$	v$_0$	v$_7$	v$_7$	v$_0$	v$_0$	v$_7$	v$_7$

where, V_0 = 000, V_1 = 100, V_2 = 110, V_3 = 010 , V_4 = 011 , V_5 = 001 , V_6 = 101 , V_7 = 111. Each switching state represents the top switch of the three phase rectifier. For example, for V_1 = 100, the top switch connected to phase A is on and other top switches which are connected to other 2 phases (B and C) are turned off.For this case, bottom switch connected to phase A is off while bottom switch connected to phase B and C are turned on.

V. MATLAB/SIMULINK MODEL BLOCKS

A model of the proposed DPC-SVM rectifier and controller system was developed using Matlab/Simulink tool. The complete block of the model developed in Simulink is as represented in Figure 3.

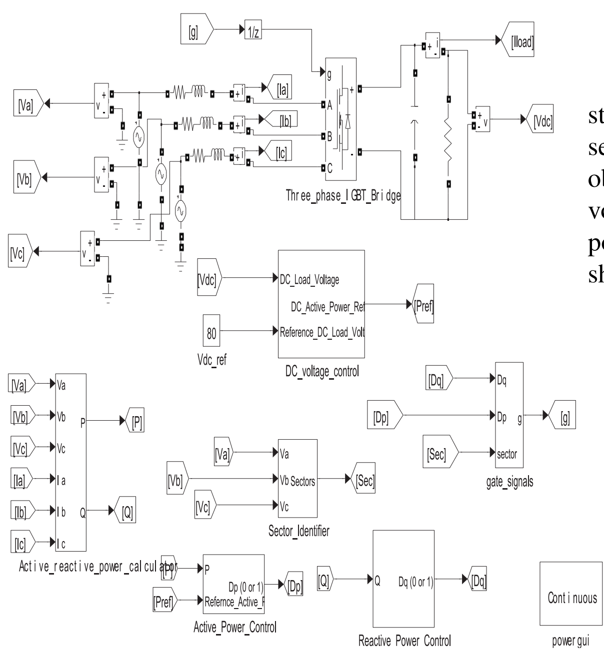

Fig. 3: Complete blocks developed in Simulink for simulation of the proposed rectifier

In the simulink blocks as shown in Figure 3, instantaneous active and reactive calculator block uses equation 1. Similarly, sector identifier block is used to determine the sector in which the voltage vector lies. Equation 12 is used for this purpose. The hysteresis band control as given in equation 18 determines the value of d_p within the active power control block which has p (active power) and p_{ref} (reference active power) as two inputs. p_{ref} is determined from the output dc voltage (V_{dc}) and reference dc voltage (V_{dcref}). Whereas, digitized signal d_q is obtained within the reactive power control block using equation 19. q_{ref} is normally set to zero for unity power factor. The gate signals are determined within gate signal block which has d_p, d_q and sectors as three inputs. Different parameters used for modeling the DPC-SVM rectifier are summarized as in Table III.

TABLE III: Parameters used for the rectifier modeling

Output DC Bus Voltage	80V
Line Inductance	2mH
Line Resistance	0.56 Ω
Load Capacitance	2350μF
Load Resistance	100 Ω
Proportional (P) Gain	4
Integral (I) gain	0.005
Hysteresis band for Active Power (H_P)	0.1
Hysteresis band for Reactive Power (H_Q)	0.1

VI. SIMULATION RESULTS

Initially, the boost rectifier is simulated for constant amplitude and frequency AC voltage with q_{ref} set at zero for UPF. From Figure 4, it can be observed that constant boosted DC regulated output voltage is obtained with UPF (i.e. zero reactive power). only a single phase voltage and current are shown in Figure 4 as all three phases are balanced.

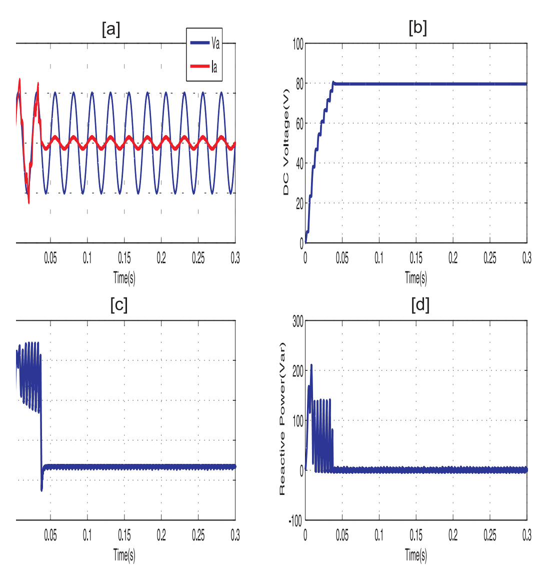

Fig. 4: [a]UPF with phase voltage and current [b]regulated and boosted DC voltage for a constant three phase generator voltage and frequency, [c] Active power and [d] reactive power

In order to test the controller response, the reference reactive power is varied during the simulation period. It can be observed as in Figure 5 that the controller quickly responses to the reference reactive power making in phase, leading and lagging the generator voltage respectively.

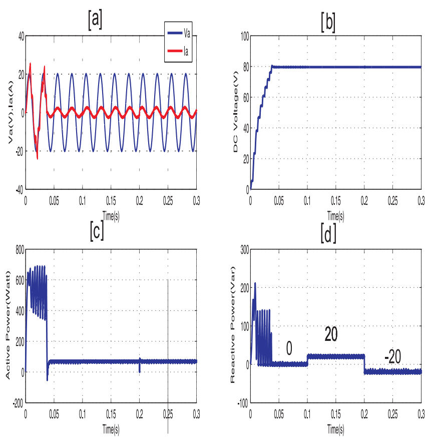

Fig. 5: [a]Phase A voltage and current, [b]DC output voltage, [c]active power and [d]reactive power when q_{ref} is set to zero, +20 VAR(at t=0.1s) and -20 VAR(at t= 0.2s)

Figure 4 and Figure 5 shows initial startup transients in the generator current. Since the capacitor is fully discharged initially, there is a large voltage difference between the input and output hence the load tries to draw a large amount of current initially. As the voltage stabilizes to a reference value, the current reduces in magnitude and is finally in phase with voltage maintaining UPF. In order to observe the controller response and reduce the initial transient in the current waveform, the load capacitor can be charged to a reference value. Precharging the capacitor close to the reference value or even lower than the reference value reduces the current transients by huge amount as shown in Figure 6 where the load capacitor is precharged to 80 V.

In order to model for variable speed wind turbine, the controller was tuned for phase voltages of 15V-50Hz, 20V-60Hz, 25V-70Hz,30V-80 Hz and 40V-100Hz. Figure 7 shows that UPF is still achieved with constant boosted DC voltage and constant active power. The start up transient in current causes the spikes in active and reactive power. This can be reduced if the output capacitor is pre charged as discussed for Figure 6.

The controller was tested for variable output load and the output responses are plotted as in Figure 8. It can be seen that the variation of load changes the output power maintaining UPF and regulating constant output DC voltage.

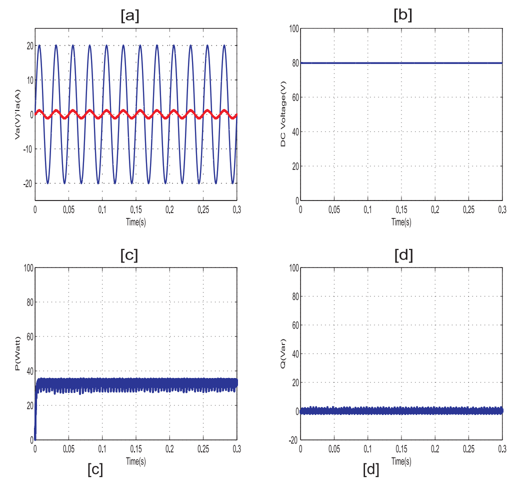

Fig. 6: [a]Phase A voltage and current, [b]DC output voltage, [c]active power and [d]reactive power after pre-charging the capacitor to the reference voltage level

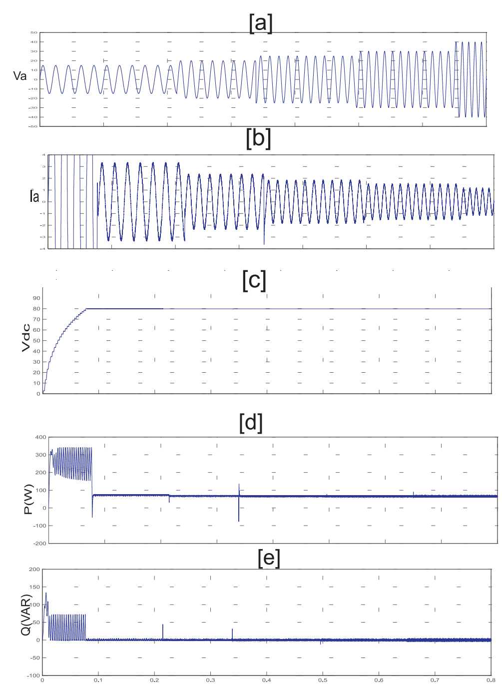

Fig. 7: [a] Phase voltage with variable amplitude and frequency,[b] Phase current,[c] Regulated DC output voltage [d] Active Power and [e] Reactive Power

VII. Conclusions

DPC-SVM can be beneficial for boosting the generator voltage with PFC. Large transients seen

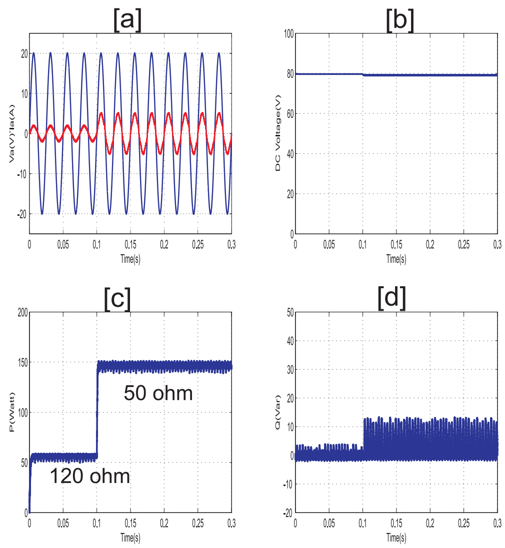

Fig. 8: Variation of Power for the step change in load [a] Phase voltage and current [b] DC regulated voltage [c] Active Power and [d] Reactive Power

start up of the turbine could be reduced by pre-charging the output capacitor. Changing output load can be an option for varying the output power out of the turbine with a constant DC boost voltage. This can be beneficial for Maximum Power Point Tracking controller for variable speed turbine in which the load (current) can be varied to reach Maximum Power Point maintaining UPF and regulated constant DC output voltage.

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